

Seismic signatures of stellar cores of solar-like pulsators: dependence on mass and age

I. M. Brandão^{1,2*}, M. S. Cunha¹, O. L. Creevey^{3,4}, J. Christensen-Dalsgaard⁵

¹ Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal

² Departamento de Matemática Aplicada, Faculdade de Ciências da Universidade do Porto, Portugal

³ Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain

⁴ Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain.

⁵ Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark

Received ??, accepted ??

Published online ?

Key words stars: oscillations – stars: interiors

Useful information from the inner layers of stellar pulsators may be derived from the study of their oscillations. In this paper we analyse three diagnostic tools suggested in the literature built from the oscillation frequencies computed for a set of main sequence models with masses between $1.0 M_{\odot}$ and $1.6 M_{\odot}$, to check what information they may hold about stellar cores. For the models with convective cores ($M \geq 1.2 M_{\odot}$) we find a relation between the frequency slopes of the diagnostic tools and the size of the jump in the sound speed at the edge of the core. We show that this relation is independent of the mass of the models. In practice, since the size of the jump in the sound speed is related to the age of the star, using these seismic tools we may, in principle, infer the star's evolutionary state. We also show that when combining two of the three diagnostic tools studied, we are able to distinguish models with convective cores from models without a convective core but with strong sound-speed gradients in the inner layers

© WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Introduction

The importance of studying the physical properties of the core of a star is connected to the fact that it is the most determinant region for the star's evolution. Although stars with masses similar to the Sun ($M \sim 1 M_{\odot}$) have radiative cores, those slightly more massive ($M > 1 M_{\odot}$) may develop a convective core at some stages of their evolution on the main sequence. Since convection implies chemical mixing, the evolution of these stars is severely influenced by the presence, and the extent, of the convective core.

Stellar oscillations can provide useful information about the interior of pulsating stars. For example, at the edge of a convective region, the derivatives of the sound speed suffer rapid variations that leave particular signatures in the oscillation frequencies (Basu et al. 1994; Gough 1990; Monteiro et al. 1994; Roxburgh & Vorontsov 1994). Several tools have been developed in order to infer the properties of the interior of a star. The most common tools are the large and small separations. The first corresponds to the average frequency spacing between modes of consecutive radial order but with the same spherical degree, and provides an estimate of the mean stellar density (Cox 1980). The second corresponds to the average spacing between modes of consecutive radial order but with spherical degrees that differ by 2. It is sensitive to the chemical composition in the deep interior, tracing the stellar evolution-

ary state (Däppen et al. 1988). The expected signature of large convective cores on the small frequency separations has been considered by Roxburgh & Vorontsov (2001) and Roxburgh & Vorontsov (2003). Cunha & Metcalfe (2007) carried out a theoretical analysis based on the properties of the oscillations of stellar models slightly more massive than the Sun and derived the expected signature of a small convective core on the oscillation frequencies.

With the recent launch of the Kepler satellite hundreds of stars will be continuously monitored in search of stellar oscillations to a very high degree of precision. So, several questions can be raised: Can we detect the signature of a small convective core on the oscillation frequencies from photometric data? What would be the dependence of this signature on the stellar mass and physical parameters? What is the precision required on the individual frequencies in order to infer the signature of a convective core? In this work we will address these questions.

2 Method

We started by computing a set of main sequence evolutionary tracks, with masses varying from 1.0 to $1.6 M_{\odot}$ in steps of $0.1 M_{\odot}$, using the 'Aarhus STellar Evolution Code', (ASTEC; Christensen-Dalsgaard 2008a). Core overshoot was included, with an overshoot distance of $\alpha_{\text{ov}} = 0.25$, in units of the pressure scale height; the overshoot region was assumed fully mixed and adiabatically stratified.

* e-mail: isa@astro.up.pt

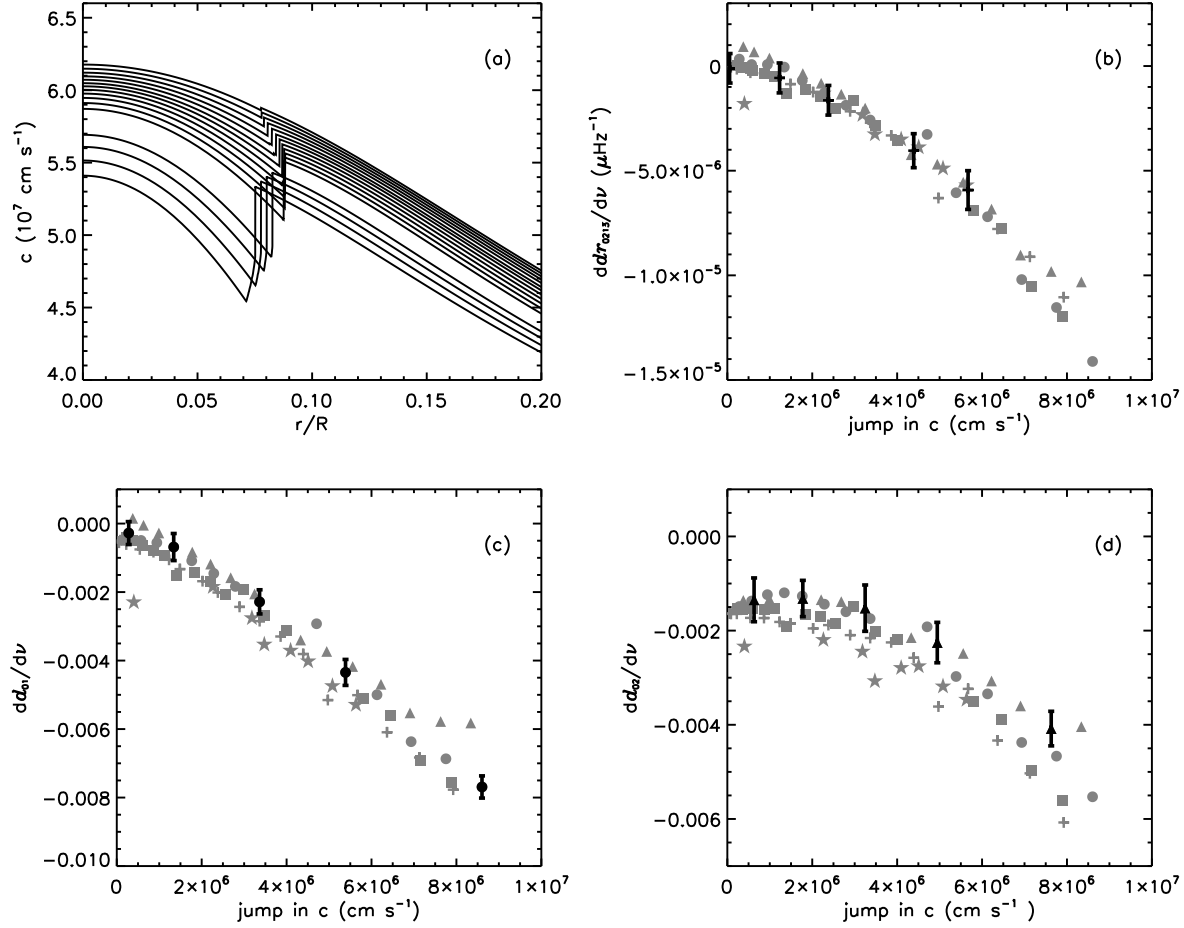


Fig. 1 Panel (a): sound-speed profile in the inner layers of a $M = 1.4 M_{\odot}$ models with different ages from 0.2 Gyr (top curve) to 3.6 Gyr (bottom curve). The slopes of the dr_{0213} (panel (b)), d_{01} (panel (c)) and d_{02} (panel (d)) diagnostic tools as a function of the size of the jump in the sound speed at the edge of the convective cores. Models with masses $M = 1.2 M_{\odot}$ are represented by stars, $M = 1.3 M_{\odot}$ by crosses, $M = 1.4 M_{\odot}$ by squares, $M = 1.5 M_{\odot}$ by circles, and $M = 1.6 M_{\odot}$ by triangles. The error bars are also plotted for some of the models.

We assumed an initial helium (Y) and heavy-element (Z) abundances of 0.24 and 0.02, respectively. Diffusion was not considered in this work. The physics used in the code was the same as described in Cunha & Metcalfe (2007). For some models, at different evolutionary stages, we computed the oscillation frequencies using the Aarhus adiabatic oscillation code ADIPLS (Christensen-Dalsgaard 2008b). These frequencies were then used to compute the following three diagnostic tools:

$$dr_{0213} = \frac{D_{02}}{\Delta\nu_{n-1,1}} - \frac{D_{13}}{\Delta\nu_{n,0}}, \quad (1)$$

$$d_{01} = \frac{1}{8}(\nu_{n-1,0} - 4\nu_{n-1,1} + 6\nu_{n,0} - 4\nu_{n,1} + \nu_{n+1,0}), \quad (2)$$

$$d_{02} = \nu_{n,0} - \nu_{n-1,2}, \quad (3)$$

where $\nu_{n,l}$ correspond to the model frequencies, for each spherical degree l and radial order n . The first diagnostic tool (Eq. 1) was proposed by Cunha & Metcalfe (2007)

and corresponds to a difference of ratios between the scaled small separations, $D_{l,l+2} \equiv (\nu_{n,l} - \nu_{n-1,l+2})/(4l+6)$, and the large separations $\Delta\nu_{n,l} \equiv \nu_{n+1,l} - \nu_{n,l}$ for different combinations of mode degrees. This tool isolates the signature of the core, but uses modes of degree from 0 to 3. The $l = 3$ modes are not easy to detect from space-based data. For that reason, we also considered in our study the other two diagnostic tools, d_{01} (Eq. 2) (e.g., Roxburgh & Vorontsov 2003) that only involves modes of $l = 0$ and 1 and the small separation d_{02} (Eq. 3) (Gough 1983) that involves modes of $l = 0$ and 2. The down side of the latter two diagnostic tools is that they do not isolate the signature of the core, although they may be strongly affected by it.

In the case of stars with convective cores we expect the frequency slopes of the diagnostic tools to be a measure of the jump in the sound speed at the edge of the convective core (Cunha et al., these proceedings). We plotted each di-

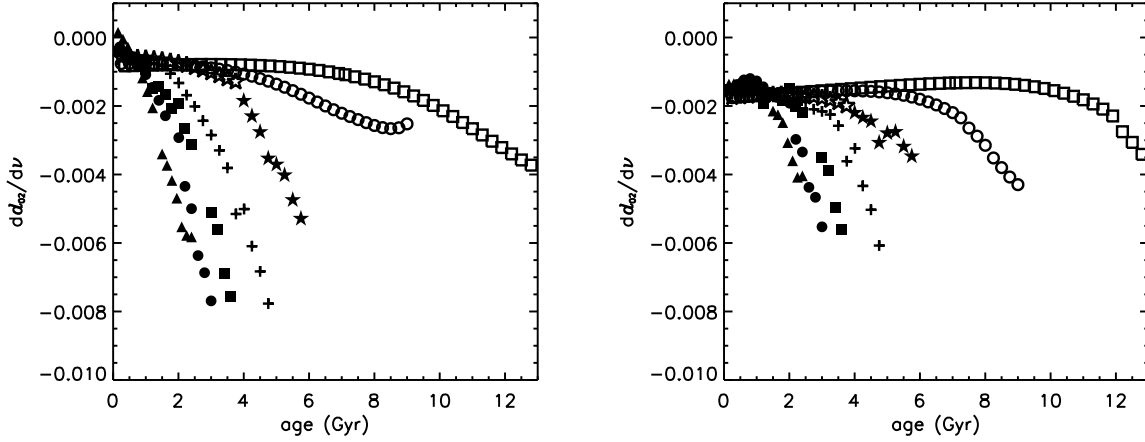


Fig. 2 The slope of the d_{01} (left plot) and d_{02} (right plot) diagnostic tools as a function of the age, for all models of our grid. Open symbols represent models without a convective core: squares for $M = 1.0 M_{\odot}$, circles for $M = 1.1 M_{\odot}$, stars for $M = 1.2 M_{\odot}$ (note that in the latter case, models older than 4 Gyr have a convective core). The other symbols are the same as in Fig. 1.

agnostic tool as a function of frequency and computed the slope by performing a linear least square fit to 10 frequencies of modes of consecutive radial orders, n , with n in the range [16,29]. The 10 radial orders effectively used in the fits were fixed for each evolutionary sequence, but varied with stellar mass. In practice, they were chosen in a way such as to capture the frequency region in which the derivatives of the diagnostic tools (the slopes) were approximately constant, and this range is also the expected observed range of frequencies. Moreover, for models with convective cores, we also computed the size of the jump of the sound speed at the edge of the convective core.

3 Results

We verified that our sequence of $1.0 M_{\odot}$ models does not show strong sound-speed gradients in the innermost layers, although the sound-speed gradients are being built up as the star evolves. These models do not have a convective core. Models with $1.1 M_{\odot}$ also do not have a convective core, but the most evolved show strong sound-speed gradients that are due to density variations. Models with $M \geq 1.2 M_{\odot}$ have convective cores and show a discontinuity of the sound speed at the core edge (Fig. 1a).

Figs. 1b-d show, for models with a convective core, slopes of the three diagnostic tools considered as a function of the size of the jump in the sound speed at the edge of the core. These three plots show a clear dependence of the slopes on the size of the jump, as expected from the work of Cunha et al. (these proceedings), this dependence being independent of the mass, at least for the physics that we considered in our set of models. In the second plot, for the quantity d_{01} , we find what seems to be a nearly linear relation.

From these results we can say that, in principle, it is possible to get a measure of the size of the jump in the sound speed at the edge of a small convective core from the observed oscillation frequencies. However, we are only able to do that if the uncertainties on the observations are such as to allow us to distinguish between slopes corresponding to different jumps. Considering a relative error of 10^{-4} on the individual frequencies, we simulated several sets of frequencies within this error. We note that observing on long timescales leads to very high precision frequency spectra. So even if the mode lifetimes are short (larger Lorentzian linewidths), the frequencies can still be determined with accuracy, if the star is "well behaved" (e.g. not a fast rotator, or a very active star). We computed the three diagnostic tools for each set of frequencies and measured their slopes. We considered the $1\text{-}\sigma$ dispersion on the slopes as an estimate of their uncertainty. The error bars are shown for some models in the three plots of Fig. 1 and confirm that one may expect to be able to set constraints on the jump in sound speed, particularly when using the dr_{0213} or d_{01} diagnostic tool. Fig. 2 shows the slopes of the d_{01} and d_{02} diagnostic tools as a function of age. As mentioned above, although our $1.1 M_{\odot}$ models do not have a convective core, they show strong sound-speed gradients in the core when significantly evolved. These gradients also have an impact on the oscillation frequencies. Thus, we then ask the question: given a value for the slope, how can we distinguish between models with strong sound-speed gradients and without a convective core, from those with a convective core that show a discontinuity in the sound speed? To address this question, and since the two diagnostic tools give different information from the interior of the star, we plotted the slopes of the d_{01} diagnostic tool as a function of the slopes of the d_{02} diagnostic tool (Fig. 3). In this diagram, in the region of small slopes it is hardly possible to distinguish between slopes, given

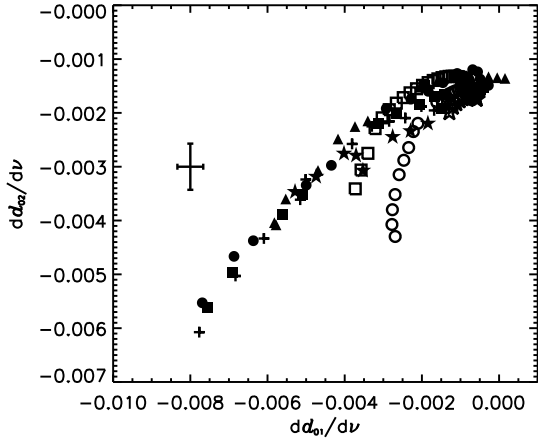


Fig. 3 The slopes of the d_{01} diagnostic tool as a function of the slopes of the d_{02} diagnostic. Symbols are the same as for Fig. 2.

the uncertainties. However, for slopes of magnitude larger than a given threshold, say $dd_{02}/d\nu < -0.002$, we see that models with strong sound-speed gradients but no discontinuity (i.e. no convective core — open symbols) are positioned differently from those with convective cores (filled symbols). We, thus, see this slope-slope diagram as a potentially very interesting tool to distinguish between stars with strong variations of sound speed in the core, yet of different origin.

4 Conclusions

We used three seismic diagnostic tools to study the cores of models of different masses and different evolutionary states. We verified that there is a relation between the frequency slopes of all of the diagnostic tools and the size of the jump in the sound speed at the edge of the convective core. In the case of the diagnostic tool, d_{01} , we find that the relation is linear. Moreover, in the case of the dr_{0213} and d_{01} diagnostic tools, the relation seems to be independent of stellar mass. Since strong sound-speed gradients may exist in evolved models of stars without a convective core, we have checked if it is possible to distinguish between those cases and the case of models with convective cores. We found that this may in principle be possible, in some cases, in a $dd_{01}/d\nu - dd_{02}/d\nu$ diagram. Further investigation is underway to check this possibility.

Acknowledgements. This work was supported by the European Helio- and Asteroseismology Network (HELAS), a major international collaboration funded by the European Commission's Sixth Framework Programme. Part of this work was carried out during IMB's visit to the Instituto de Astrofísica de Canarias (IAC). This work was also supported by the project PTDC/CTE-AST/098754/2008, the grant SFRH / BD / 41213 / 2007 funded by FCT/MCTES, Portugal. MC is supported by a Ciência 2007 contract, funded by FCT/MCTES(Portugal) and POPH/FSE (EC).

References

- Basu, S., Antia, H. M., & Narasimha, D. 1994, MNRAS , 267, 209
- Christensen-Dalsgaard, J. 2008a, Ap&SS , 316, 13
- Christensen-Dalsgaard, J. 2008b, Ap&SS , 316, 113
- Cox, J. P. 1980, Theory of stellar pulsation, Princeton University Press.
- Cunha, M. S. & Metcalfe, T. S. 2007, ApJ , 666, 413
- Däppen, W., Dziembowski, W. A., & Sienkiewicz, R. 1988, in IAU Symposium, Vol. 123, Advances in Helio- and Asteroseismology, ed. J. Christensen-Dalsgaard & S. Frandsen, 233
- Gough, D. O. 1983, Physics Bulletin, 34, 502
- Gough, D. O. 1990, in Lecture Notes in Physics, Berlin Springer Verlag, Vol. 367, Progress of Seismology of the Sun and Stars, ed. Y. Osaki & H. Shibahashi, 283
- Monteiro, M. J. P. F. G., Christensen-Dalsgaard, J., & Thompson, M. J. 1994, A&A, 283, 247
- Roxburgh, I. W. & Vorontsov, S. V. 1994, MNRAS , 268, 880
- Roxburgh, I. W. & Vorontsov, S. V. 2001, MNRAS , 322, 85
- Roxburgh, I. W. & Vorontsov, S. V. 2003, A&A, 411, 215